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Risk Aversion and CO2 Regulatory Uncertainty in Power Generation Investment: Policy and Modeling Implications

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Abstract

Our simulation considers producers in a competitive energy market. Risk averse producers face uncertainty about future carbon regulation. Investment decisions are a two-stage equilibrium problem. Initially, investment is made under regulatory uncertainty; then the regulatory state is revealed and producers realize returns. We consider taxes, grandfathered permits and auctioned permits and show that outcomes vary under risk aversion; some anticipated policies yield perverse investment incentives, in that investment in the dirty technology is encouraged. Beliefs about the policy instrument that will be used to price carbon may be as important as certainty that carbon will be priced. More generally, a failure to consider risk aversion may bias policy models of the power sector.

Keywords Electric power, risk aversion, emissions markets, climate policy

JEL Classification L11, L94, Q40, Q48, Q54

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Risk Aversion and CO_2 Regulatory Uncertainty in Power Generation Investment: Policy and Modeling Implications

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1. Introduction

We consider investors who are planning to expand in electricity generation capacity market. Investors are anticipating regulation regarding carbon dioxide emissions in the future but do not know when it will be passed. Investors face large amount of sunk costs investing in a particular technology, and are inclined to be risk averse towards the investments. Regulation of the sector to protect the global climate seems likely at some point in the U.S., and anticipated costs are large relative to past regulatory interventions.

We allow investors to anticipate different kinds of policies, and we consider the implications of their investment choices for outcomes in the presence and absence of the anticipated regulation. Numerical results from a stochastic two-stage equilibrium model suggest that in the presence of risk aversion, some carbon instruments will introduce perverse incentives favoring investment in dirty generation technology. Thus the choice between grandfathering and auctioning permits has implications for efficiency and costs, as well as the usual distributional effects.

Investments in generation capacity have lasting consequences for costs and emissions. The median coal-fired generation facility in the United States is over forty years old [1]. There are significant fixed costs to building capacity, and switching a given plant from one fuel to another is usually expensive or impractical. Risk is increasingly important in this setting, and thus analyses that assume certainty (or the ability to switch from one stream of annualized power plant costs to another at zero or low cost) can be misleading. Financial hedges in this setting are also less available due to difficulties in the credit markets and investor reluctance to insure firms against downside risks that are likely to correlate with significant economic costs and to affect most firms in this setting simultaneously [2; 3; 4].

In particular, risk averse decision makers facing uncertain regulation may make investment choices that lead to a persistently inefficient generation mix for the decades ahead. Reinelt and Keith [5] find that the "interaction of regulatory uncertainty with irreversible investment raises the social cost of carbon abatement by as much as 50%" in this setting with risk neutral investors[1]. Delay can lead to investment in dirty technology in hopes that future policies will favor existing coal plants, or to support of lobbying efforts designed to minimize regulation. This overinvestment is socially suboptimal and may be suboptimal for business interests relative to a scenario with *either* regulation *or* no regulation with certainty, especially if rent-seeking costs are high. We examine the effects of incorporating risk and uncertainty and consider the implications for the broader policy debate and associated modeling efforts.

The two-stage model considers investments by two types of firms, one building highly polluting but low variable cost capacity (coal-fired plants), and the other building low polluting but high variable cost capacity (natural gas plants). Our efforts focus on the changing incentives for each kind of investment and are not an effort to realistically depict a single firm's investment

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[1] Their calculations do not allow for the possibility of retrofits for conventional plants.

portfolio; given homogenous technology, allowing multiple firms to invest in both technologies will yield identical choices across firms, which complicates exposition without adding new insights. Firms with the capacity to hedge two technologies against each other will have different responses to regulatory uncertainty than those that cannot, but the change in price and cost ratios will work in the same direction for each type of investment. The first stage decision is made in the face of regulatory uncertainty as to whether or not a given carbon policy will be imposed. In the second stage, the regulation is either imposed or not, and a short-run market equilibrium among the players results. Price-taking behavior is assumed throughout.

As expected, regardless of how the allowances are allocated in a cap and trade system, risk neutral firms make the same decisions in terms of capacity and output, even though different allowance allocation and distribution schemes yield varying profits. Uncertain risk neutral firms choose an investment mix that is optimal for neither policy, maximizing the expected payoff of investment strategies based on their beliefs about the likelihood of the regulatory regime. Risk averse investors hedge their bets even further to reduce their losses in the 'bad' outcome, which is regulation in the case of a tax or auction and no regulation if permits are grandfathered.

As intuition suggests, risk neutral suppliers facing possible regulation build more gas and less coal-fired generation capacity than in a business-as-usual (BAU) no regulation scenario, regardless of what form the potential carbon regulation takes. Risk aversion complicates matters: if allowances are grandfathered risk aversion increases investment in coal – which pays off in the bad, unregulated state – and decreases it in gas relative to the risk neutral solution. If allowances are auctioned, the reverse is true. This result is driven by the gains from increased distribution of free permits to coal plants under grandfathering. Under our parameterizations, coal plant profits are higher under regulation, broadly consistent with observation of the European Union Emissions Trading System [6]. In contrast, an auction or carbon tax provides a more direct signal to follow: firms see the rise in the expected relative price of coal under regulatory uncertainty and the more risk averse they are, the more they invest in less carbon-intensive generation that will pay off in the regulated state.

This analysis focuses on firms who are uncertain about the passage of a specific regulation. It seems natural as well to consider the uncertainty about the form of eventual regulation, including uncertainty regarding the details of permit allocation and distribution schemes. We have formulated and solved models representing the situation in which firms are uncertain about the form of regulation. This limits the ability of firms to hedge regulatory risks by adjusting investment strategies, and thus the effects of risk aversion are mixed and small relative to the results presented here.

While it is difficult to observe levels of risk aversion and risk management strategies empirically (Chetty and Chetty and Szeidl [7; 8] show how consumer insurance choices, for instance, are insufficient to deduce levels of consumer risk aversion, and firm insurance strategies cannot generally be observed to any significant degree), our results suggest that modest amounts of aversion to risk that are hedged via investments in durable physical capital will impact the ability of the U.S. power sector to meet emissions goals efficiently.

In most of the literature on electricity market modeling generally as well as on carbon policy in particular, firm risk attitudes are not captured. Models common in this setting, e.g., NEMS [9] and IPM [10] are deterministic, considering a single regulatory scenario and perfect foresight. This reflects the extreme complexity of these models; here we have simplified much that is important in policymaking to focus on the implications of risk and uncertainty in isolation.

We believe this to be important; Niemayer [11] shows that older and dirtier coal plants are especially vulnerable to changes in carbon emissions rules over the next five to ten years, and this trend seems unlikely to change. Barbose [12] investigates the plans of western utility companies and shows that most of them currently make choices based on some expectation of future carbon regulations. Our broader purpose is to consider the implications of risk-fearing investors who make durable investments under uncertainty.

There is a literature on modeling capacity investment under uncertainty with risk neutral actors; Kanudia and Loulou [13] and Hu and Hobbs [14] simulate choices using the stochastic MARKAL model (with risk neutrality and multiple policy scenarios), and Zhuang and Gabriel [15] solve a similar problem as a mixed complementarity problem (MCP). (A MCP is the problem of finding column vectors (X,Y) that satisfy conditions $f(X,Y) \leq 0$, $X \geq 0$, $f(X)^T X = 0$, and $g(X,Y) = 0$, where $f(\cdot)$ and $g(\cdot)$ are vector valued functions with the same dimensions as X and Y, respectively.) Fleten, Hoyland et al. [16] and Unger [17] consider optimal investment by individual risk averse generators facing uncertain output prices who are 'penalized' for net losses. Tseng and Barz [18] and Liu [19] evaluate optimal operations for a company facing uncertain prices and Patino-Echeverri, Morel et al. [20] studies the investment choices of a firm facing uncertain pricing. This work takes price processes as exogenous, leaving aside questions of how risk aversion might affect market equilibria.

Researchers have also studied financial hedges against risk in electricity markets. Dahlgren, Liu et al. [21] consider 'financial engineering' and output price risk management in power markets, again for a single firm. Willems and Joris [22] builds on work on forward-spot market equilibria by Bessembinder and Lemmon [23] to evaluate financial hedges with risk aversion and varying liquidity constraints and degrees of market completeness. However, that work does not consider impacts on equilibrium investments in the power sector. Ralph and Smeers [24] present an initial attempt to do so, considering diversity of risk attitudes among investors, while Ehrenmann and Smeers [25] adopt an approach related to ours. The latter paper adopts the extreme case of minimization of CVaR (Conditional Value-at-Risk) to represent risk aversion, and did not consider intermediate levels of risk aversion (for instance by maximizing expected profit minus a weight times CVaR).

We do not model the relative merits of various carbon policies in the broader economy as in Parry [26; 27], who argues for taxes over grandfathering permits on the grounds that a tax is more transparent and could have offsetting tax-interaction effects in other markets. Nonetheless, this work strengthens this conclusion by noting that anticipating a tax or auction system spurs investment in low carbon technologies while the reverse is true of grandfathered permits. Nor do we allow for carbon policy to affect economy-wide allocations of investment in technology and labor as in Peretto [28] – our results represent an equilibrium only in power markets.

This work also contributes to the established literature on the benefits of regulatory certainty; even risk neutral investors in durable technology are more efficient in the certainty case, and for many outcomes investors and society pay higher costs under risk aversion. Bergara, Henisz et al. [29] analyze this in the electricity sector; see also Levy and Spiller [30], Lavey [31], Porter and van der Linde [32] and Porter [33], among others.

The paper is structured as the following: section 2 introduces the model and the methodology in subsections, where the mathematical model is defined, followed by an analytical and a numerical example; section 3 discusses more about the numerical example's results and we present both risk neutral and risk averse results; section 4 concludes.

2. Methods and Models

We consider a carbon tax scenario and two approaches to a cap and trade scheme in which allowances are distributed freely (based on some rule that is independent of future investment and operating decisions) ("grandfathering"), or allocated by government auction. To be specific, with a cap and trade rule, there will be an emissions cap for all generators in the region and all emission allowances are distributed or auctioned. In the tax scenario, the amount of the tax will be equivalent to the value of emission permits derived from the cap-and-trade scenario. Firms are uncertain regarding the enactment of a given rule. We assume competitive markets and do not discuss demand growth or fuel price uncertainty, transmission and capacity markets, climate risk aversion, or consumer risk aversion in this simplified analysis. We do include demand variability, in the form of a distribution of demand functions over the year within the second stage (e.g., peak vs baseload demands). This distribution is known ahead of time to all market players, and is the reason why in equilibrium there is a mix of high- and low-variable cost generation technologies in the market. This assumption is standard in power market modeling [34].

In our model investors make initial investment decisions – whether to invest and how much - without knowing the state of the world in the next stage. In the following period, in the absence of regulation, everything remains the same; if there is regulation, it takes one of several forms. Permits are then either grandfathered or auctioned or a tax is imposed, and the allowances can be traded among firms in a competitive market.

In the investment decision process, the investors develop a portfolio of production plans for electricity production in both scenarios, given investments prior to the state of the world being revealed. We first assume 'No regulation' scenario cost and demand functions including demand variability, which is a fundamental feature of electricity economics, resulting in the need for a mix of capital-intensive baseload versus high fuel cost peaking capacity [35]. The degree of intra-annual demand variability will influence the equilibrium mix, with greater variability shifting the mix towards the latter. In the 'Regulation' scenario, the distribution of demand functions is unchanged but costs reflect the addition of equilibrium permit prices. Both the electricity price and the permit price are solved by market clearing conditions. Firms must make investment choices to maximize their utility in expectation over all regulatory scenarios. Utility is a function of profit in the second stage, net of fixed costs and summed over the demand periods. (Thus, investors are assumed to be risk averse only with respect to regulatory scenarios, and not the variability of demand within the year. This is reasonable, since hour-to-hour demand variability is predictable and contributes little to variability in annual net revenues, whereas regulatory uncertainty results in large uncertainty in annual net revenues. Ehrenmann and Smeers [25] makes the same assumptions).

Risk attitudes are modeled using a risk averse utility function as the objective function of the firms. Utility is a function of profit, and the more concave the function is, the greater the degree of risk aversion. That concavity results in a lower expected utility for an uncertain profit than for a certain profit when their expected values are identical. We consider how varying degrees of risk aversion affect the equilibrium results by changing the Arrow-Pratt coefficient in a Constant Absolute Risk Averse (CARA) utility function given by:

$$U(\pi) = m - n \cdot e^{-R\pi}, \quad for\ n > 0, R > 0 \qquad (1)$$

Firms thus have a constant absolute risk aversion (R) in total profit (π). A larger R indicates that the agent is more risk averse. The extreme case of risk neutrality can be modeled by directly using expected profit as the objective. Both m and n in (1) are set to 1 for simplicity in our model, and do not affect the solutions.

Suppliers maximize expected utility under a set of constraints; consumers maximize consumer surplus in each demand period in the second stage; and the markets for energy and allowances clear.

The Karush-Kuhn-Tucker (KKT) conditions for each market player's optimization problem together with the market clearing conditions define an equilibrium problem expressed as a mixed complementarity problem [36]. This allows for flexibility in the form and interaction of the constraints and is common in modeling for this policy setting [34; 37]. We use the PATH solver in GAMS to find equilibria under various assumptions.

2.1 Model Definition

Initially, we summarize the formulation of the model with two risk averse firms.[2] The sets, parameters, variables and equations used in the model are shown in Table 1. The model simulates the firms' investment problem when they face uncertainty in the carbon policy scheme: either there will be no regulation in the next stage (with probability PR_{nreg}), or a cap and trade carbon emission permit scheme (with probability $PR_{reg} = 1\text{-}PR_{nreg}$).[3]

For firms:

For the firm using fuel k, annualized profit in scenario i is defined as π_{ik}:

$$\pi_{ik} = \sum_j HR_j \cdot q_{ijk} \cdot (p_{ij}^e - MC_{ik}) - CC_k \cdot cap_k - Z_i \cdot p_{reg}^c \cdot emit_{reg,k} \tag{2}$$

Risk neutral firms maximize expected profit π_k, and risk averse firms maximize expected utility U_k where the utility function U_{ik} is defined according to equation (1):

$$Max \quad \pi_k = \sum_i PR_i \cdot \pi_{ik} \quad \text{(for risk neutral firms)} \tag{3}$$

$$Max \quad U_k = \sum_i PR_i \cdot U_{ik} = 1 - \sum_i PR_i \cdot e^{-R \cdot \pi_{ik}} \qquad \text{(for risk averse firms)} \tag{4}$$

$$s.t. \quad q_{ijk} - cap_k \le 0 \qquad \forall\ i, j, k \qquad (\mu_{ijk}) \tag{5}$$

$$\sum_j E_k \cdot HR_j \cdot q_{reg,jk} - emit_{reg,k} \le E_k^{gf} \qquad (\lambda_{reg,k}) \tag{6}$$

This model format is flexible in the sense that when the allowances are auctioned, $E_k^{gf} = 0$. Any rule that distributes free allowances to firms in a manner that is independent of the firms' decisions can be modeled by adjusting this parameter.

The KKT conditions associated with risk averse firms are as follows. (The symbol ⊥ means that the two conditions are orthogonal, i.e., $0 \le x \perp f(x) \le 0$ is equivalent to $0 \le x$, $f(x) \le 0$, and $x \times f(x) = 0$.)

$$0 \le q_{ijk} \perp R \cdot PR_i \cdot e^{-R \cdot \pi_{ik}} \cdot HR_j \cdot (p_{ij}^e - MC_{ik}) - \mu_{ijk} - Z_i \cdot E_k \cdot HR_j \cdot \lambda_{reg,k} \le 0 \qquad \forall i, j, k \tag{7}$$

$$0 \le cap_k \perp \sum_i PR_i \cdot R \cdot e^{-R \cdot \pi_{ik}} \cdot (-CC_k) + \sum_{i,j} \mu_{ijk} \le 0 \qquad \forall\ k \tag{8}$$

$$0 \le emit_{reg,k} \perp -PR_{reg} \cdot R \cdot e^{-R \cdot \pi_{reg,k}} \cdot p_{reg}^c + \lambda_{reg,k} \le 0 \qquad \forall\ k \tag{9}$$

$$0 \le \mu_{ijk} \perp q_{ijk} - cap_k \le 0 \qquad \forall\ i, j, k \tag{10}$$

$$0 \le \lambda_{reg,k} \perp \sum_j E_k \cdot HR_j \cdot q_{reg,jk} - E_k^{gf} - emit_{reg,k} \le 0 \qquad \forall\ k \tag{11}$$

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[2] For convenience, we set up the problem with a gas-fired firm and a coal-fired firm; allowing firms to have a mixture of technology would not change the nature of the results.

[3] We do not show the case of a carbon tax here, but the basic model formulation would change little. In the tax case, the price for the carbon emission is the tax (TAX_i) itself, instead of the carbon price (p^c_{reg}) generated from the cap-and-trade system, as in the cap-and-trade's scenario.

Consumers maximize their surplus CS_i:

$$Max \quad CS_i = \sum_j HR_j \cdot [(\Phi_{ij} \cdot d_{ij} - \frac{1}{2}\frac{\Phi_{ij}}{\Psi_{ij}} \cdot d_{ij}{}^2) - p^e_{ij} \cdot d_{ij}] \tag{12}$$

$$s.t. \quad d_{ij} \geq 0 \qquad \forall\ i, j \tag{13}$$

The consumers' KKT conditions are:

$$0 \leq d_{ij} \perp \Phi_{ij} - \frac{\Phi_{ij}}{\Psi_{ij}} \cdot d_{ij} - p^e_{ij} \leq 0 \qquad \forall\ i, j \tag{14}$$

The market clearing conditions for energy and emissions are, respectively:

$$\sum_k q_{ijk} = d_{ij} \qquad \forall\ i, j \qquad (p^e_{ij}) \tag{15}$$

$$\sum_{j,k} E_k \cdot HR_j \cdot q_{reg,jk} = E^{cap} \qquad (p^c_{reg}) \tag{16}$$

2.2 Analytical Results

In this section, we show that under certain conditions, market equilibrium prices, emissions, and generation mix are invariant with respect to the allowance distribution and allocation scheme or tax, if firms are risk neutral. Subsequent numerical results show that this does not hold under risk aversion.

Three policy environments are considered:

i. Cap and trade policy with auctioned allowances;

ii. Cap and trade policy with free allowances, with a fixed number of grandfathered (i.e., distributed independently of the firm's decisions) permits;

iii. Carbon tax, where the tax is exogenously set to the allowance price obtained from the auction-based allowance trading model (i).

[Proposition 1] For risk neutral firms in a competitive electricity market, under a fixed emission cap that is binding: (i) and (ii) yield the same values for investment and operation of the plant. For risk neutral firms any permit equilibrium (i) is a tax equilibrium (iii) [4].

First we develop the equilibrium conditions for risk neutral operators who either buy auctioned allowances, are given a fixed number of allowances for free, or some combination of the two approaches. We then derive the first order conditions for an equivalent carbon tax model. When we model risk averse firms, the former equivalence no longer holds. Nevertheless, we can show certain equivalences between the model with auctioned emission permits (model (i)) and an equivalent carbon tax model (model (iii)). The proof is below.

Proof of Proposition 1: Firstly, the existence of an equilibrium is guaranteed for models (i), (ii) and (iii), if, (a): the strategy set is non-empty, convex and compact; and (b): the utility function is quasi concave [45]. The games satisfy the two conditions: first, an equilibrium will never have more capacity than the peak demand under zero price, otherwise there would be unused capacity and its owner could increase profit by not building that capacity. Consequently, our decision variables have a lower and upper bound, and thus the strategy set satisfies condition (a). Second, our utility function, the exponential function of profit, is a concave utility function, satisfying (b).

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[4] The existence of the Nash Equilibrium is shown in the proof for proposition 1.

Part I: *Equivalence of (i) and (ii) in investment, energy demand, and prices.*

If the price of emissions is positive (otherwise the overall equilibrium problem is trivial), the emission constraint for firms (equation (6)) will hold as an equality (By contradiction, if it held as a strict inequality while the emissions price was positive, then the firm could increase profit by decreasing $emit_{reg,k}$ without affecting any other decision.):

$$\sum_j E_k \cdot HR_j \cdot q_{reg,jk} - emit_{reg,k} = E_k^{gf} \qquad (\lambda_{reg,k}) \tag{17}$$

Simplify the model by substituting $emit_{reg,k}$ into the objective (3), then the objective and constraints (originally equations (3), (5) and (6)) for firms in model (i) and (ii) become:

$$\begin{aligned} Max \quad \pi_k = \sum_i PR_i \cdot [\sum_j HR_j \cdot q_{ijk} \cdot (p^e_{ij} - MC_{ik}) - CC_k \cdot cap_k - \\ Z_i \cdot p^c_{reg} \cdot (\sum_j E_k \cdot HR_j \cdot q_{reg,jk} - E_k^{gf})] \end{aligned} \quad , \tag{18}$$

plus constraint (5). The associated KKT conditions are:

$$0 \le q_{ijk} \perp PR_i \cdot HR_j \cdot (p^e_{ij} - MC_{ik} - Z_i \cdot E_k \cdot p^c_{reg}) - \mu_{ijk} \le 0 \qquad \forall\ i, j, k \tag{19}$$

$$0 \le cap_k \perp -CC_k + \sum_{i,j} \mu_{ijk} \le 0 \qquad \forall\ k \tag{20}$$

plus condition (10). The consumer's condition and market clearing conditions (14)-(16) remain the same.

The resulting equilibrium problem ((10), (14)-(16), (19), (20)) is independent of E^{gf}_k, so the decision variables of capacity, energy output, and quantity demanded (as well as prices) are not a function of E^{gf}_k. Thus, if the allowances are totally grandfathered ($E^{gf} = E^{cap}$), or auctioned ($E^{gf} = 0$), or distributed by another allocation rule, the solutions do not change and models (i) and (ii) yield the same generator decisions and market prices. Other variables, including the permit purchases $emit_{reg,k}$ and consequent profits for firms in different scenarios, differ.

Part II: Equivalence of (i) and (iii). The tax model (iii) is based upon this definition of firm profit:

$$\pi_{ik} = \sum_j HR_j \cdot q_{ijk} \cdot (p^e_{ij} - MC_{ik} - TAX_i \cdot E_k) - CC_k \cdot cap_k \tag{21}$$

where the TAX_i is assumed to equal 0 under scenario $i = nreg$ while equaling p^e_{reg} from models (i) and (ii) if $i = reg$. In the risk neutral case, firms' objective and constraint are:

$$Max \quad \pi_k = \sum_i PR_i \cdot [\sum_j HR_j \cdot q_{ijk} \cdot (p^e_{ij} - MC_{ik} - TAX_i \cdot E_k) - CC_k \cdot cap_k] \quad , \tag{22}$$

plus constraint (5).

The KKT condition with regard to the plant output variables then becomes:

$$0 \le q_{ijk} \perp PR_i \cdot HR_j \cdot (p^e_{ij} - MC_{ik} - TAX_i \cdot E_k) - \mu_{ijk} \le 0 \quad \forall\ i, j, k \tag{23}$$

The overall equilibrium problem ((10), (14), (15), (20), (23)) consists of condition (23) plus conditions (20) and (10) for firms, (14) for consumers, and (15) for energy market clearing, as in models (i) and (ii). Condition (16), market clearing for emissions, is omitted because we instead assume an exogenous tax.

Thus, models (i), (ii) and (iii) are comprised of the same sets of conditions except for one of the firms' condition (equation (19) vs. equation (23)); in addition, model (i) and (ii) have one more market clearing condition than model (iii) (equation (16)). Thus, if we show the equivalence of equations (19) and (23), we show that all model (i) and (ii) solutions are a subset of the solutions to model (iii). To show the equivalence of (19) and (23), it is sufficient to show the following equation holds:

$$PR_i \cdot HR_j \cdot E_k \cdot TAX_i = PR_i \cdot HR_j \cdot Z_i \cdot E_k \cdot p^c_{reg} \tag{24}$$

This is true by assumption: when the realized scenario is 'No regulation' (i.e., $Z_{nreg} = 0$, and $TAX_{nreg} = 0$), then (24) is satisfied trivially; when the scenario is 'Regulation', (24) holds since $Z_{reg} = 1$ and the tax equals the permit price.

Therefore, model (i) and (ii)'s solutions are a subset of model (iii)'s solution. The emissions permit models (i) and (ii)'s solution also satisfy the conditions for the tax model (iii) (but not necessarily the other way, if there are multiple equilibria for model (iii)) because the latter's equilibrium conditions are a subset of the formers'.) Additionally, if the solution for model (iii) is unique, then model (i), (ii) and model (iii) are equivalent, yielding the same decision variables, prices, and surpluses for all market participants. This completes the proof.

> **[Proposition 2]**: Assume risk averse firms in a competitive market. Consider models (i), with auctioned permits, and (iii) with an equivalent carbon tax. Then the risk averse market equilibrium solutions for model (i) are a subset of the solution set for model (iii) in terms of the decision variables and prices, and the solutions are identical when model (iii) has a unique equilibrium.

This proposition can be viewed as a generalization of that proved in Newell, Pizer et al. [38] to the case of risk aversion in firms. We show that model (i) generates equilibria in terms of decision variables and prices which are a subset of model (iii)'s decision variable and price solution set.

Proof of Proposition 2: Model (i) is formulated by equations (4)-(6). Assuming, as in Proposition 1, that the firms emissions permit trading constraint (6) holds as an equality, then for model (i), the profit is defined as in (18) plus setting $E^{gf}_k = 0$, i.e.:

$$\pi_{ik} = \sum_j HR_j \cdot q_{ijk} \cdot (p^e_{ij} - MC_{ik} - Z_i \cdot p^c_{reg} \cdot E_k) - CC_k \cdot cap_k \tag{25}$$

The risk averse firms' problem reduces to (4) and (5) and the KKT conditions are:

$$0 \le q_{ijk} \perp PR_i \cdot R \cdot HR_j \cdot e^{-R\pi_{ik}} \cdot (p^e_{ij} - MC_{ik} - Z_i \cdot p^c_{reg} \cdot E_k) - \mu_{ijk} \le 0 \quad \forall\, i, j, k \tag{26}$$

plus conditions (8) and (10) for firms, (14) for consumers, and the two market clearing conditions (15) and (16). Equilibrium is defined as ((8), (10), (14), (15), (16), (26)).

Meanwhile, model (iii) has profit formulated as in (21), objective (4) and constraint (5). So the equilibrium conditions associated with model (iii) are:

$$0 \le q_{ijk} \perp PR_i \cdot R \cdot HR_j \cdot e^{-R\pi_{ik}} \cdot (p^e_{ij} - MC_{ik} - TAX_i \cdot E_k) - \mu_{ijk} \le 0 \quad \forall\, i, j, k \tag{27}$$

plus firms' conditions (8) and (10), consumer condition (14), and the energy market clearing condition (15). Equilibrium is defined as ((8), (10), (14), (15), (27)).

First note the equivalence of (26) and (27). This follows from our assumption that the allowance price in the tax model (iii) is set to the level that would occur in the auctioned permits model (i), as in Proposition 1. Since all the other equilibrium conditions of model (iii) are also in model (i) while model (i) has one more market clearing condition (16) than model (iii), then any solution to model (i) will also satisfy the equilibrium conditions in (iii). Further, if model (iii) does not have multiple solutions, models (i) and (iii) are equivalent and this completes the proof.

Under the assumption of risk neutrality, different allowance allocation and distribution schemes generate the same capacity and operational strategies, although firms realize different profits under different schemes. This is because the specific scheme determines how rents are allocated, but does not change the marginal costs and benefits of investments. Under risk aversion, investors' strategies are sensitive to the amount of economic rents they will receive – as shown in the propositions, the rent affects the marginal utility of profit for risk averse investors– and thus grandfathering or auctioning permits provides very different incentives. Since solutions under risk aversion are less tractable analytically, we examine them computationally. We do not consider the tax scenario separately below, since the auction yields identical results.

2.3 Computational Application

To illustrate how firms with different risk attitudes will invest in the settings defined above, consider a single power market with the following characteristics (fuller details of the parameters are shown in Table 1; market demand parameters are shown in the appendix):

We assume equal probability for the future scenarios: a given rule under cap-and-trade policy is realized or not. There are two firms investing in the market; one a coal-fired plant investor and the other a gas-turbine investor. They face a deterministic inverse demand function as in equation (28) in appendix 1, which reflects peak and off-peak demands for 24 periods over a one-year horizon (8760 hours). The coal-fired plant has higher capital costs (140,000$/MW/yr) but lower variable costs (40$/MWh, variable costs exclusive of carbon permit costs); the gas-turbine has lower capital costs (80,000$/MW/yr) but higher variable costs (65$/MWh). However, the coal plant has high CO_2 emissions (1 tons/MWh) compared to the gas plant (0.5 tons/MWh)[5]. If emissions are regulated, then the government will set an emission cap at 80% of the BAU baseline.

We model two methods for distribution of initial permits under grandfathering which assigns allowances based on existing capacity (rule I[6]), or existing generation (rule II[5]). Under both rules, the free allowance amounts are exogenous to choices made by firms in the stochastic market equilibria, so this is a true grandfathering scheme, not an updating scheme. In our parameterization, rule II gives relatively more allowances to coal-fired plant than rule I: the gas firm is granted 0.53 million tons/yr emission allowances and the coal firm is granted 8.63 million tons/yr. In contrast, rule I grants 4.14 million tons/yr to the gas plant and 5.02 million tons/yr to the coal plant. The firms' utility function is equation (1).

As shown above, the initial distribution rule will not affect the risk neutral firms' investment and operating decisions nor market prices, but for risk averse firms, it might. To analyze the impact of risk aversion in more details, we present deterministic and stochastic equilibrium models; in the former we solve for 'No regulation' with certainty outcomes and regulation with certainty outcomes, and in the latter consider how increasing levels of risk aversion affect outcomes when a regulation may or may not be implemented in the next period.

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[5] The assumptions reflect current literatures for policy models of the energy sector (or broader). We have investigated reports (e.g., from International Energy Agency (IEA) [39] and [40]); as well as several peer-reviewed articles (e.g., Odenberger, Unger et al. [41] and Schwarz [42], etc.) We believe our assumptions fall reasonably in the range of the up-to-date modeling assumptions for this sector.

[6] Mathematically, under rule I, the allocated emission for firm k is: $E_k^{gf1} = \frac{E_k \cdot cap_k^0}{\sum_f E_f \cdot cap_k^0} \cdot E^{gf}, \forall k$;

under rule II, $E_k^{gf2} = \frac{\sum_j E_k \cdot q_{jk}^0 \cdot HR_j}{\sum_{j,f} E_f \cdot q_{jf}^0 \cdot HR_j} \cdot E^{gf}, \forall k$, where $cap^0{}_k$, $q^0{}_{jk}$ indicates the capacity/output decisions as solved from the BAU case (please refer to table 1 for notation details).

Table 1. Model definitions

Sets		***Parameters***	
i	Scenario indicator, denoted as '*reg*' for 'Regulation' and '*nreg*' for 'No regulation'.	Φ_{ij}, Ψ_{ij}	Parameters for the linear demand function in scenario *i*, period *j*.
j	Time period indicator within a scenario of the year, representing levels of demand (e.g., peak vs. baseload).	CC_k	Annualized capacity cost for the firm k ($/MW/yr).
k	Generation fuel/firm type indicator (natural gas or coal-fired firm), denoted as '*g*' and '*c*', respectively.	MC_{ik}	Variable cost for the firm k in scenario i ($/MWh).
Decision Variables		PR_i	Probability of being in scenario *i*.
d_{ij}	Quantity of electricity demanded in scenario *i*, demand period *j* of stage two (MW).	HR_j	Hours in period j (hrs/yr).
q_{ijk}	Quantity of energy supplied in scenario *i*, period *j* by the firm using fuel *k* (MW).	E_k	Emission rate of fuel/firm *k* (tons/MWh).
cap_k	Capacity constructed for firm *k* (MW).	E^{cap}	Emission cap for the entire market (tons/yr).
$emit_{reg,k}$	Net emission permit purchase if *i*=*reg* by the firm using fuel *k* (tons/yr).	E^{gf}	Total grandfathered allowances in the market (tons/yr).
Lagrange multipliers		E^{gf}_k	Grandfathered allowances allocated to firm *k* (tons/yr).
μ_{ijk}	Lagrange multiplier for the capacity constraint for firm *k* in scenario *i*, period *j* ($/MW/yr).	TAX_i	Exogenous tax in scenario *i* in the emissions tax model ($/ton).
p^e_{ij}	Market clearing electricity price in scenario *i*, period *j* ($/MWh).	Z_i	Scenario indicator. $Z_i = 1$, if *i* = *reg* and $Z_i = 0$ if *i* = *nreg*.
$\lambda_{reg,k}$	Lagrange multiplier for the emission constraint for firm *k* ($/ton).	R	Arrow-Pratt risk aversion coefficient.
p^c_{reg}	Equilibrium emission permit price under the *reg* scenario ($/ton).		

3. Model Solutions and Discussion

A few key results are summarized in Table 2. Tables 3 through 5 show fuller solutions for the cap and trade scheme – Table 3 shows model solutions where emission allowances are auctioned; Tables 4 and 5 show solutions where emission allowances are grandfathered.

3.1. Uncertainty and risk neutrality

Initially we solve for the market's baseline emission level, the 'Deterministic no regulation' solution; we define the emissions cap as 80% of that level.[7] This baseline case corresponds to Column 1, Table 2 and Column 2 from Tables 3 through 5. At baseline, the gas plant installs 1890 MW capacity, the coal plant installs 1146 MW and together they serve demand ranging from 595-3036 MW. The gas plant operates at full capacity (1890 MW) in peak demand periods and shuts down when demand is low, because gas-turbine generated power has higher marginal costs. The coal plant runs at full capacity (1146 MW) for the peak, and provides all the power when demand is less than or equal to its capacity. With the emission factors we assumed, the gas plant emits 0.5 million tons/yr CO_2 ($=\sum_j q_{nreg,j,g}$ MW * HR_j hrs/yr * 0.5 ton/MWh). Similarly, the coal plant emits 8.6 million tons/yr CO_2 ($=\sum_j q_{nreg,,j,c}$ MW * HR_j hrs/yr * 1 ton/MWh). Thus, the total CO_2 emission baseline is 9.1 million tons/yr.

If regulation is certain (Column 2, Table 2 and Column 3, Tables 3-5), investment in gas

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[7] The results shown are all for a 20% reduction in emissions; we also performed the analysis for a 50% reduction, with results showing similar trends but, as would be expected, of greater magnitude. These are available from the authors upon request, but are not reported as we feel that the 20% results are more relevant to the current policy discourse. Risk aversion with regards to fixed capital investments should reflect the expected regulatory timeline, and a 20% reduction within the lifetime of a new power plant is certainly plausible in the United States at present.

generation increases and coal decreases, with an equilibrium installed capacity of 2329 MW and 608 MW, respectively. Emissions intensity falls 17%, and total CO_2 emissions fall to 7.3 million tons/year. Total quantity of power supplied drops by about 4% relative to the baseline as prices rise. As shown in Proposition 1, these results do not depend on the specific form of regulation.

For risk neutral suppliers, shown in Columns 3-4 of Table 2 and Column 4 of Tables 3-5, compared to the baseline, if investors are certain the regulation will be implemented, the gas plant increases its capacity and investments in coal-fired capacity decline. If regulation is uncertain, both changes are moderated. This finding is consistent with our intuition regarding uncertainty and holds for regulations that impose a permit auction and for those that grandfather permits.

As this is a long run equilibrium problem without scale economies, risk neutral firms realize zero expected profits in the auction model. Thus, when the emissions cap is 80% of the baseline emissions, in the auction case, the gas firm sees a profit of 4.9 million \$/yr in the 'No regulation' scenario and -4.9 million \$/yr in the 'Regulation' scenario; the coal firm sees a profit of 62.0 million \$/yr in the unregulated scenario and -62.0 million \$/yr in the regulated scenario. Both lose money under regulation, as power prices rise insufficiently to cover the cost of allowances.

However, when the government allocates allowances for free to risk neutral firms, expected profits are positive and equal to the value of the free allowances. The gas firm earns 4.9 and 16.4 million \$/yr in the 'No regulation' and 'Regulation' scenario, respectively; the coal company earns \$62 million in the 'No regulation' scenario and \$283 million in the 'Regulation' scenario. The total expected profit of the two plants is thus \$183 million. The total expected economic rent associated with the free allowances is also 183 million \$/yr (=7.3 million ton/yr * 50\$/ton * 0.5, with 0.5 the probability of being in regulation). Both firms earn more under regulation because each receives valuable allowances for free, even though total electricity sales across the two firms fall due to higher energy prices, which arise because the opportunity cost of allowances is partially passed through to the consumer. (Indeed, this was the experience in the EU after the implementation of CO_2 trading in 2005, see [6]).

Since regardless of how allowances are distributed, risk neutral firms facing the same emissions cap make the same investment and operating decisions, the same quantities supplied and power prices emerge in equilibrium. With emissions capped at 80% of the baseline, risk neutral firms facing regulatory uncertainty make the following choices: the gas firm builds 1973 MW capacity and the coal firm builds 992 MW. The demand weighted power price is 82 \$/MWh if the regulation is not implemented and 115 \$/MWh if it is. However, there are differences in the net permits purchased by each firm and their individual profits under regulation for alternative allowance distribution schemes. Thus, the coal firm makes a loss under regulation with auctioned permits, but earns profits if allowances are grandfathered. This difference in profits affects the equilibrium investments and prices for risk averse investors.

3.2. Adding risk aversion

In contrast, when firms are risk averse, how emission allowances will be managed affects investment choices under uncertainty, as shown in Columns 5-6 of Table 2. When all allowances are auctioned, risk averse firms build more (relatively clean) gas capacity and less (relatively dirty) coal capacity than risk neutral firms. This trend intensifies as risk aversion increases (Figure 1 and Table 3). The reverse happens if allowances are grandfathered under either of the proposed rules (Figures 2 and 3 and Tables 4 and 5)—the gas firm builds less capacity and the coal plant more. This is because the relatively carbon intensive coal plant will receive more of the rents associated with free permits than the gas plant, making it more attractive in the event of regulation. Thus, the effect of risk aversion is ambiguous, interacting with the choice of how allowances are allocated. While the focus of political debate over whether allowances should be granted freely or auctioned has been on who gets the resulting economic rents, if risk aversion matters, there are also implications for generation mix, costs, and emissions.

Figure 1[8]: Effect of risk aversion on capacity decisions, auctioned allowances, 80% emission cap, equal scenario probability

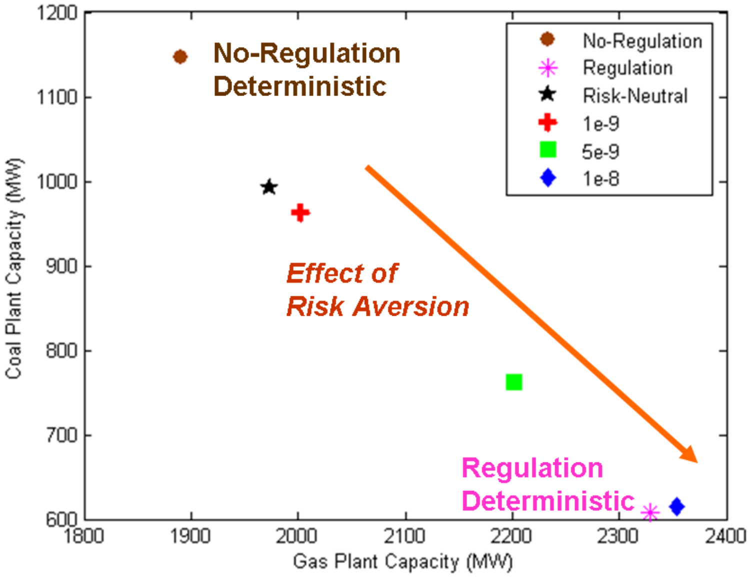
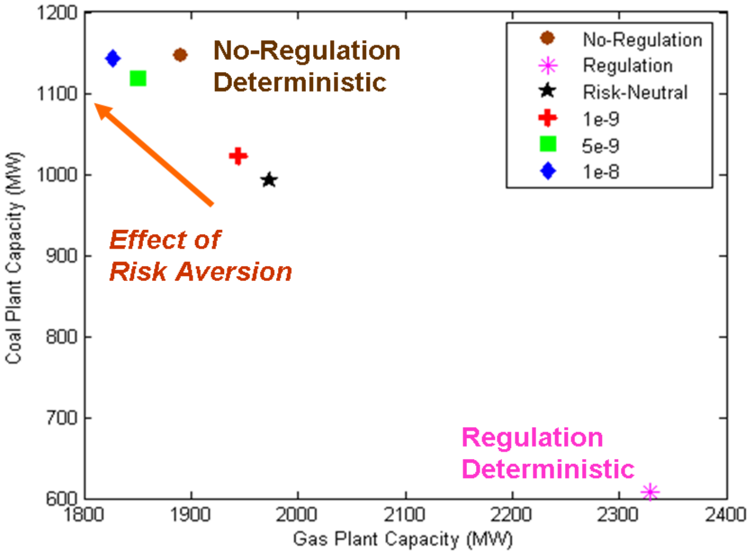


Figure 2: Effect of risk aversion on capacity decisions, grandfathered emission allowances, allocation rule II, 80% emission cap, equal scenario probability



The intuition behind the observed interaction between risk aversion and investment choices is as follows. A risk averse actor puts more relative weight on the 'bad' (less profitable) scenarios in the decision process. The greater the degree of risk aversion, the more weight placed on that bad scenario and, as a result, the more the firm's investment choice will resemble the decision made if that 'bad' scenario is certain. This trend is shown by the arrows in Figures 1-3. Which scenario will be the 'bad' scenario will depend on the specific policy considered. If emission permits are grandfathered, firms receive a 'free' asset and profits are higher than under 'No regulation'. Thus, risk aversion moves firms' decisions towards the less profitable, deterministic 'No regulation' case – increasing coal capacity. However, when allowances are auctioned, the government is allocated

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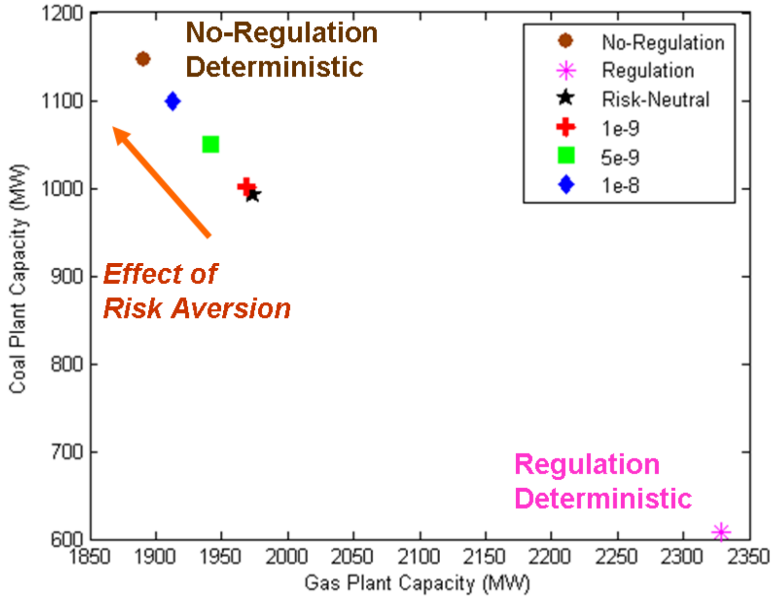
[8] Numbers in figure 1-3 refer to risk aversion coefficients; 1e-9 reflects the mildest level of risk aversion and 1e-8 the highest level shown.

the new asset instead of firms, and the cost of production is increased under regulation, making the regulated scenario the ‘bad’ one. As energy prices do not increase enough to compensate, firms are worse off under regulation with auctioned permits, and they hedge against that eventuality in their capacity expansion choices by investing in the relatively clean gas-turbine technology.

Figure 3: Effect of risk aversion on capacity decisions, grandfathered emission allowances, allocation rule I, 80% emission cap, equal scenario probability



This partly explains why under grandfathering, greater risk aversion actually increases the total amount of investment. The reason is that increased risk aversion, as noted above, causes individual investors to shift their investments closer to what would occur in the less profitable of the two deterministic scenarios. Under rule I, this is the “No regulation” scenario, which has more total capacity.

Babcock, Choi et al. [43] discuss the difficulty of interpreting (or providing intuition for) the degree of risk aversion based on the CARA coefficient. Bickel and Smith [44] finds that financial stress and the cost of liquidity do not drive high levels of risk aversion in firms. However, the implicit weights placed on the ‘bad’ outcome by investors under the given scenarios do not seem unreasonable.

For example, in the auction setting, the gas firm with a risk aversion coefficient of 5×10^{-9} (Column 6, Table 3) makes decisions equivalent to putting a weight of 49% on the ‘No regulation’ (good) scenario and 51% on the ‘Regulation’ (bad) scenario. With allowances grandfathered using the emissions rule, the gas firm with $R = 5\times10^{-9}$ (Table 4, Column 6) puts 51.2% implicit weight on the ‘No regulation’ (bad) scenario and 48.8% on the ‘Regulation’ (good) scenario. The coal plant puts an implicit weight of 65% on ‘No regulation’ and 35% on ‘Regulation.’ As risk aversion increases, the gas firm’s implicit weight for the ‘bad’ scenario rises from 51.2% to 51.6% and the coal firm’s from 65% to 76.7%.

The permit market is competitive, so the permit price equals the marginal cost of control. In this case, this is the cost of reducing emissions by one additional ton by switching from coal to gas generation. In Table 4 Column 6 (the middle parameterization of risk aversion), the permit price is 50$/ton. If an emissions reduction was achieved by lowering demand, that could reflect a slight price increase in the last (lowest demand) period. The price at that time is $90/MWh, and the marginal fuel is coal, which costs $40/MWh; so the loss of willingness-to-pay (net of fuel savings) is \$50/MWh, which equals the price of emissions allowances (cost per ton emission reduction, i.e., \$50/MWh/1ton/MWh = \$50/ton). This allowance price is also consistent with a pure supply-side emissions reduction strategy of substituting gas for coal: reducing emissions by one ton under a constant quantity demanded would be accomplished by increasing gas generation by two MWh and lowering generation by coal by an equal amount, lowering emissions by 2 MWh*(1 - 0.5 tons/MWh) = 1 ton. This would increase fuel costs by 2 MWh*(65 \$/MWh – 40 \$/MWh) = \$50, again equal to the allowance price.

The equilibrium energy price (demand weighted) in the 'No regulation' scenario rises with increasing risk aversion when allowances are auctioned, but drops with increasing risk aversion when allowances are grandfathered. (Note, however, that unregulated prices are always lower than prices under regulation). These trends in unregulated prices arise because risk aversion results in increased investment in cleaner, higher marginal cost capacity when investors anticipate an auction scheme; consequently, if regulation does not materialize, this costly capacity is marginal in more hours, resulting in higher prices. In contrast, the greater amount of dirty, low marginal cost technology built by investors fearing the absence of a lucrative grandfathering program results in this capacity providing the marginal unit of power in more hours in the no regulation scenario, lowering average prices. For the relatively mild emissions reduction shown here, the permit price is not very sensitive to either risk attitudes or emission allocation rules. Figures 1-3 show capacity decisions under different levels of risk aversion in investors facing an 80% cap implemented by permit auction or grandfathering.

The change in capacity mix due to risk aversion affects not only expected costs in the stochastic equilibria, but also realized emissions in the 'No regulation' scenario in those equilibria. (Emissions in the regulated scenario are unaffected by definition since the same cap is assumed for all regulated cases). In the stochastic equilibrium under risk neutrality with auctioned allowances, realized 'No regulation' emissions are 96% of the emissions at the deterministic baseline; as risk aversion is introduced and increased, unregulated emissions drop to between 81 and 95% of the base case. The reverse is true under grandfathering; as risk aversion increases, the installed capacity mix becomes dirtier, and so emissions in the absence of a policy increase relative to the risk neutral case. Emissions under risk aversion with the generation rule (rule II) range from 97 to ~100% of baseline emissions when the anticipated policy is not realized in the second stage; the range is from 97 to 99% under the capacity rule (rule I). Thus, the interaction of risk aversion and allowance distribution via grandfathering or auction has not only cost implications but also emissions effects in the period prior to implementation of a policy program, though the exact allocation rule for grandfathered allowances has relatively small impacts in the parameterization used here.

Ongoing work is needed to determine how risk aversion might be incorporated in large-scale policy models. One extension would be to consider multiple decision stages for investments, which would allow for both the option of delaying investment until regulatory uncertainties are at least partially resolved, and for later adjustments in capacity. Although computational challenges make this work beyond the scope of the current paper, we hypothesize that the irreversibility of capacity investment would still imply that increased risk aversion would bias firms towards optimal investments under the least profitable scenarios. Defensible heuristics or efforts to estimate the degree of risk aversion empirically might strengthen future modeling efforts. Further, this work abstracts from known important features of the policy setting, including market power, renewable portfolio standards, and engineering risks related to grid reliability. A more detailed specification of the plant itself could enable consideration of plant lifecycles and scale effects in technology – this would ideally include the dynamics of investment choices when the investor already owns heterogenous capital stock for electricity generation; the choice of when to retire old capital so as to delay decision making under uncertainty is likely to be important in this setting.

4. Conclusions

For risk averse generators, capacity and cost outcomes are sensitive to the distribution and allocation scheme for allowances, since this determines whether the 'Regulation' or 'No regulation' scenario is more profitable. While risk neutral firms will make the same investment decision in terms of decision variables (capacities, supplies, prices, demands), regardless of how the emission allowances are treated (grandfathered or auctioned) and which rule is applied in the grandfathering case, risk averse firms will not: if carbon is taxed or allowances are auctioned, investment in clean generation increases with the degree of risk aversion as firms self-insure against the possibility of costly regulation. On the other hand, if allowances are allocated to producers for free, investment in dirty generation rises relative to the risk-neutral case and, under our parameterizations, approaches the level expected under the guaranteed 'No regulation' scenario. Risk averse generators position themselves to hedge against the possibility that lucrative regulation will not be implemented in the next period.

With risk aversion, emissions in the 'No regulation' scenario are lower for auctioned permits and higher with grandfathering. Consumer prices under regulation are not very sensitive to distribution/allocation of permits in the regulated scenario; however, if the proposed regulation is not implemented, consumer prices rise with risk aversion if an auction is anticipated and fall if grandfathering is anticipated. Complete social welfare calculations are not possible without valuing avoided climate damages (and damages associated with other pollutants for each technology), but these results imply losses of productive and allocative efficiency in power markets.

The magnitude of the effect of risk aversion on the equilibrium generation mix will, of course, depend on assumptions concerning the available types of generation and their characteristics. We have considered the two most popular types of generation capacity installed in the last twenty years in the US; in other simulations, not shown here for the sake of brevity, we have also included renewable generation. The same trend occurs: risk aversion pushes each market party's investments in the direction of the scenario that is least profitable. Other assumptions might result in larger or smaller effects, but we anticipate the same qualitative results.

Our finding has policy implications: distribution schemes do not just determine who gets rents from creating emissions rights. The kind of regulatory framework that industry anticipates will affect their choices in potentially perverse ways. Additionally, if political considerations make regulators unable or unwilling to impose carbon dioxide restrictions without helping dirty sectors, it might be preferable to find ways to rebate the funds raised from an auction in ways that do not encourage carbon-intensive generation investment. More generally, we find that a failure to consider risk and risk aversion may bias models of this sector and others, especially where durable capital investments limit adjustment options.

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Table 2: Summary of key results

		Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
		Deterministic Equilibria		Stochastic - Risk Neutral		Stochastic - Risk Averse*	
		Baseline**	Regulation	Regulation Scenario	Regulation Scenario	No Regulation Scenario	Regulation Scenario
Gas Firm Capacity (MW)	Auction	1890	2329	1973	1973	2201	2201
	GF (Allocation Rule II)		2329	1973	1973	1850	1850
	GF (Allocation Rule I)		2329	1973	1973	1941	1941
Coal Firm Capacity (MW)	Auction	1146	608	992	992	763	763
	GF (Allocation Rule II)		608	992	992	1118	1118
	GF (Allocation Rule I)		608	992	992	1051	1051
Demand Weighted Price ($/MWh)	Auction	75	107	82	115	88	115
	GF (Allocation Rule II)		107	82	115	77	115
	GF (Allocation Rule I)		107	82	115	80	115
Gas Firm Total Quantity Supplied (Million MWh)	Auction	1.1	4.1	1.6	3.9	3.0	3.9
	GF (Allocation Rule II)		4.1	1.6	3.9	1.1	3.9
	GF (Allocation Rule I)		4.1	1.6	3.9	1.3	3.9
Coal Firm Total Quantity Supplied (Million MWh)	Auction	8.6	5.4	8.0	5.4	6.6	5.4
	GF (Allocation Rule II)		5.4	8.0	5.4	8.5	5.4
	GF (Allocation Rule I)		5.4	8.0	5.4	8.3	5.4
Gas Firm Total Emission (Million Ton/yr)	Auction	0.53	2.0	0.79	2.0	1.5	2.0
	GF (Allocation Rule II)		2.0	0.79	2.0	0.56	2.0
	GF (Allocation Rule I)		2.0	0.79	2.0	0.67	2.0
Coal Firm Total Emission (Million Ton/yr)	Auction	8.6	5.3	8.0	5.4	6.6	5.4
	GF (Allocation Rule II)		5.3	8.0	5.4	8.5	5.4
	GF (Allocation Rule I)		5.3	8.0	5.4	8.3	5.4
CO_2 Permit Price ($/Ton)	Auction	--	35	--	50	--	50
	GF (Allocation Rule II)		35	--	50	--	50
	GF (Allocation Rule I)		35	--	50	--	50
Gas Firm Profit (Million $/yr)	Auction	0.0	0.0	4.9	-4.9	5.7	-5.4
	GF (Allocation Rule II)		14.9	4.9	16.4	4.5	16.6
	GF (Allocation Rule I)		116.0	4.9	161.0	3.1	159.0
Coal Firm Profit (Million $/yr)	Auction	0.0	0.0	62.0	-62.0	99.2	-47.6
	GF (Allocation Rule II)		242.0	62.0	283.0	19.5	275.0
	GF (Allocation Rule I)		141.0	62.0	139.0	42.0	134.0
Total Emission per Output (Tons/MWh/yr)	Auction	0.95	0.79	0.92	0.79	0.84	0.79
	GF (Allocation Rule II)		0.79	0.92	0.79	0.94	0.79
	GF (Allocation Rule I)		0.79	0.92	0.79	0.93	0.79
Average Generation Cost ($/MWh)	Auction	74.9	107.3	75.0	122.0	77.5	120.5
	GF (Allocation Rule II)		79.8	75.0	82.5	74.4	83.3
	GF (Allocation Rule I)		79.8	75.0	82.5	74.8	83.1
Average Variable Generation Cost ($/MWh)	Auction	42.7	78.1	44.1	90.0	47.9	90.0
	GF (Allocation Rule II)		50.7	44.1	50.6	42.9	50.6
	GF (Allocation Rule I)		50.7	44.1	50.6	43.5	50.6
Average Fixed Generation Cost ($/MWh)	Auction	32.2	29.2	30.9	31.9	29.6	30.4
	GF (Allocation Rule II)		29.2	30.9	31.9	31.5	32.8
	GF (Allocation Rule I)		29.2	30.9	31.9	31.4	32.6

*: Risk averse results are for the middle parameterization of risk; Column 6 in subsequent tables.

**: Baseline solutions are presented and are independent of policy schemes listed in the left.

Table 3: Example of solutions found with 80% emission cap, auctioned allowances in a competitive market

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
	Deterministic Model		Stochastic Model			
Regulation Environment/Risk Attitude	Baseline	Regulation	Neutral	$1x10^{-9}$	$5x10^{-9}$	$1x10^{-8}$
Gas Firm Capacity (MW)	1890	2329	1973	2003	2201	2354
Coal Firm Capacity (MW)	1146	608	992	962	763	615
Peak Power Price *nreg* ($/MWh)	798	--	802	802	802	802
Offpeak Power Price *nreg* ($/MWh)	40	--	40	40	40	40
Peak Power Price *reg* ($/MWh)	--	804	802	802	802	802
Offpeak Power Price *reg* ($/MWh)	--	75	90	90	90	86
Demand Weighted Price *nreg* ($/MWh)	75	--	82	83	88	89
Demand Weighted Price *reg* ($/MWh)	--	107	115	115	115	113
Peak Demand *nreg* (MWh)	3036	--	2966	2965	2964	2968
Offpeak Demand *nreg* (MWh)	595	--	595	595	595	595
Peak Demand *reg* (MWh)	--	2937	2966	2965	2964	2968
Offpeak Demand *reg* (MWh)	--	574	564	564	564	567
Gas Firm Peak Output *nreg* (MWh)	1890	--	1973	2003	2201	2354
Gas Firm Offpeak Output *nreg* (MWh)	0	--	0	0	0	0
Coal Firm Peak Output *nreg* (MWh)	1146	--	992	962	763	615
Coal Firm Offpeak Output *nreg* (MWh)	595	--	595	595	595	595
Gas Firm Peak Output *reg* (MWh)	--	2329	1973	2003	2201	2354
Gas Firm Offpeak Output *reg* (MWh)	--	0	146	564	0	0
Coal Firm Peak Output *reg* (MWh)	--	608	992	962	763	642
Coal Firm Offpeak Output *reg* (MWh)	--	574	419	0	564	567
Gas Firm Permit Purchase (million tons/yr)	--	2.03	1.96	1.96	1.96	1.98
Coal Firm Permit Purchase (million tons/yr)	--	5.30	5.37	5.37	5.37	5.35
Permit Price ($/ton)	--	35	50	50	50	45.71
Gas Firm Profit *nreg* (million $/yr)	0	--	4.9	5.0	5.7	5.7
Coal Firm Profit *nreg* (million $/yr)	0	--	62.0	68.4	99.2	85.7
Gas Firm Profit *reg* (million $/yr)	--	0	-4.9	-5.0	-5.4	-5.1
Coal Firm Profit *reg* (million $/yr)	--	0	-62.0	-60.1	-47.6	-27.7
Gas Firm Utility *nreg*	--	--	--	0.0	0.0	0.1
Coal Firm Utility *nreg*	--	--	--	0.1	0.4	0.6
Gas Firm Utility *reg*	--	--	--	0.0	0.0	-0.1
Coal Firm Utility *reg*	--	--	--	-0.1	-0.3	-0.3
Gas Firm Expected utility	--	--	--	0.0	0.0	0.0
Coal Firm Expected utility	--	--	--	0.0	0.1	0.1
Gas Firm Certainty Equivalent (thousand $/yr)	--	--	--	12.5	75.7	144.0
Coal Firm Certainty Equivalent (million $/yr)	--	--	--	2.1	12.6	14.2
Gas Firm Emissions *nreg* (million ton/yr)	0.53	--	0.79	0.86	1.50	2.09
Coal Firm Emissions *nreg* (million ton/yr)	8.63	--	8.03	7.88	6.55	5.37
Gas Firm Emissions *reg* (million ton/yr)	--	2.03	1.96	1.96	1.96	1.98
Coal Firm Emissions *reg* (million ton/yr)	--	5.30	5.37	5.37	5.37	5.35
Total Emissions *nreg* (million ton/yr)	9.2	--	8.8	8.7	8.1	7.5
Total Emissions *reg* (million ton/yr)	--	7.3	7.3	7.3	7.3	7.3
Producer Surplus *nreg* (million $/yr)	0.0	--	66.9	73.4	104.8	93.2
Producer Surplus *reg* (million $/yr)	--	0.0	-66.9	-65.1	-53.0	-32.8
Consumer Surplus *nreg* (billion $/yr)	4.48	--	4.41	4.40	4.35	4.34
Consumer Surplus *reg* (billion $/yr)	--	4.18	4.11	4.11	4.11	4.13

Table 4: Example of solutions found with 80% emission cap, grandfathering allowances (allocation rule II) in a competitive market

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
	Deterministic Model		Stochastic Model			
Regulation Environment/Risk Attitude	Baseline	Regulation	Neutral	$1x10^{-9}$	$5x10^{-9}$	$1x10^{-8}$
Gas Firm Capacity (MW)	1890	2329	1973	1945	1850	1827
Coal Firm Capacity (MW)	1146	608	992	1021	1118	1143
Peak Power Price *nreg* ($/MWh)	798	--	802	802	802	802
Offpeak Power Price *nreg* ($/MWh)	40	--	40	40	40	40
Peak Power Price *reg* ($/MWh)	--	804	802	802	802	802
Offpeak Power Price *reg* ($/MWh)	--	75	90	90	90	90
Demand Weighted Price *nreg* ($/MWh)	75	--	82	81	77	75
Demand Weighted Price *reg* ($/MWh)	--	107	115	115	115	115
Peak Demand *nreg* (MWh)	3036	--	2966	2966	2968	2970
Offpeak Demand *nreg* (MWh)	595	--	595	595	595	595
Peak Demand *reg* (MWh)	--	2937	2966	2966	2968	2970
Offpeak Demand *reg* (MWh)	--	574	564	564	564	564
Gas Firm Peak Output *nreg* (MWh)	1890	--	1973	1945	1850	1827
Gas Firm Offpeak Output *nreg* (MWh)	0	--	0	0	0	0
Coal Firm Peak Output *nreg* (MWh)	1146	--	992	1021	1118	1143
Coal Firm Offpeak Output *nreg* (MWh)	595	--	595	595	595	595
Gas Firm Peak Output *reg* (MWh)	--	2329	1973	1945	1850	1827
Gas Firm Offpeak Output *reg* (MWh)	--	0	531	559	511	0
Coal Firm Peak Output *reg* (MWh)	--	608	992	1021	1118	1143
Coal Firm Offpeak Output *reg* (MWh)	--	574	33	5	53	564
Gas Firm Permit Purchase (million tons/yr)	--	1.6	1.5	1.5	1.5	1.5
Coal Firm Permit Purchase (million tons/yr)	--	-1.6	-1.5	-1.5	-1.5	-1.5
Permit Price ($/ton)	--	35	50	50	50	50
Gas Firm Profit *nreg* (million $/yr)	0	--	4.9	4.8	4.5	4.3
Coal Firm Profit *nreg* (million $/yr)	0	--	62.0	50.7	19.5	4.9
Gas Firm Profit *reg* (million $/yr)	--	14.9	16.4	16.4	16.6	16.5
Coal Firm Profit *reg* (million $/yr)	--	242	283	281	275	274
Gas Firm Utility *nreg*	--	--	--	0.0	0.0	0.0
Coal Firm Utility *nreg*	--	--	--	0.0	0.1	0.0
Gas Firm Utility *reg*	--	--	--	0.0	0.1	0.2
Coal Firm Utility *reg*	--	--	--	0.2	0.7	0.9
Gas Firm Expected utility	--	--	--	0.0	0.1	0.1
Coal Firm Expected utility	--	--	--	0.1	0.4	0.5
Gas Firm Certainty Equivalent (thousand $/yr)	--	--	--	10.6	10.4	10.2
Coal Firm Certainty Equivalent (million $/yr)	--	--	--	159.0	109.0	67.6
Gas Firm Emissions *nreg* (million ton/yr)	0.5	--	0.8	0.7	0.6	0.5
Coal Firm Emissions *nreg* (million ton/yr)	8.6	--	8.0	8.2	8.5	8.6
Gas Firm Emissions *reg* (million ton/yr)	--	2.03	1.96	1.96	1.96	1.96
Coal Firm Emissions *reg* (million ton/yr)	--	5.30	5.37	5.37	5.37	5.37
Total Emissions *nreg* (million ton/yr)	9.2	--	8.8	8.9	9.1	9.2
Total Emissions *reg* (million ton/yr)	--	7.3	7.3	7.3	7.3	7.3
Producer Surplus *nreg* (million $/yr)	0.0	--	67.0	55.5	24.0	9.2
Producer Surplus *reg* (million $/yr)	--	256.5	299.5	297.7	291.7	290.0
Consumer Surplus *nreg* (billion $/yr)	4.5	--	4.4	4.4	4.5	4.5
Consumer Surplus *reg* (billion $/yr)	--	4.2	4.1	4.1	4.1	4.1

Table 5: Example of solutions found with 80% emission cap, grandfathering allowances (allocation rule I) in a competitive market

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
	Deterministic Model		Stochastic Model			
Regulation Environment/Risk Attitude	Baseline	Regulation	Neutral	$1x10^{-9}$	$5x10^{-9}$	$1x10^{-8}$
Gas Firm Capacity (MW)	1890	2329	1973	1969	1941	1913
Coal Firm Capacity (MW)	1146	608	992	1002	1051	1099
Peak Power Price *nreg* ($/MWh)	798	--	802	802	801	799
Offpeak Power Price *nreg* ($/MWh)	40	--	40	40	40	40
Peak Power Price *reg* ($/MWh)	--	804	802	802	801	799
Offpeak Power Price *reg* ($/MWh)	--	75	90	90	90	90
Demand Weighted Price *nreg* ($/MWh)	75	--	82	81	80	78
Demand Weighted Price *reg* ($/MWh)	--	107	115	115	115	115
Peak Demand *nreg* (MWh)	3036	--	2966	2971	2992	3012
Offpeak Demand *nreg* (MWh)	595	--	595	595	595	595
Peak Demand *reg* (MWh)	--	2937	2966	2971	2992	3012
Offpeak Demand *reg* (MWh)	--	574	564	564	564	564
Gas Firm Peak Output *nreg* (MWh)	1890	--	1973	1969	1941	1913
Gas Firm Offpeak Output *nreg* (MWh)	0	--	0	0	0	0
Coal Firm Peak Output *nreg* (MWh)	1146	--	992	1002	1051	1099
Coal Firm Offpeak Output *nreg* (MWh)	595	--	595	595	595	595
Gas Firm Peak Output *reg* (MWh)	--	2329	1973	1969	1941	1913
Gas Firm Offpeak Output *reg* (MWh)	--	0	0	130	146	0
Coal Firm Peak Output *reg* (MWh)	--	608	992	1002	1051	1099
Coal Firm Offpeak Output *reg* (MWh)	--	574	564	434	419	564
Gas Firm Permit Purchase (million tons/yr)	--	-1.3	-1.4	-1.4	-1.4	-1.3
Coal Firm Permit Purchase (million tons/yr)	--	1.3	1.4	1.4	1.4	1.3
Permit Price ($/ton)	--	35	50	50	50	50
Gas Firm Profit *nreg* (million $/yr)	0.0	--	4.9	4.5	3.1	1.7
Coal Firm Profit *nreg* (million $/yr)	0.0	--	62.0	58.0	42.0	24.4
Gas Firm Profit *reg* (million $/yr)	--	116.0	161.0	160.0	159.0	158.0
Coal Firm Profit *reg* (million $/yr)	--	141.0	139.0	138.0	134.0	130.0
Gas Firm Utility *nreg*	--	--	--	0.0	0.0	0.0
Coal Firm Utility *nreg*	--	--	--	0.1	0.2	0.2
Gas Firm Utility *reg*	--	--	--	0.1	0.5	0.8
Coal Firm Utility *reg*	--	--	--	0.1	0.5	0.7
Gas Firm Expected utility	--	--	--	0.1	0.3	0.4
Coal Firm Expected utility	--	--	--	0.1	0.3	0.5
Gas Firm Certainty Equivalent (thousand $/yr)	--	--		79.4	66.2	51.9
Coal Firm Certainty Equivalent (million $/yr)	--	--		97.2	82.8	64.0
Gas Firm Emissions *nreg* (million ton/yr)	0.5	--	0.8	0.8	0.7	0.6
Coal Firm Emissions *nreg* (million ton/yr)	8.6	--	8.0	8.1	8.3	8.5
Gas Firm Emissions *reg* (million ton/yr)	--	2.0	2.0	2.0	2.0	2.0
Coal Firm Emissions *reg* (million ton/yr)	--	5.3	5.4	5.4	5.4	5.4
Total Emissions *nreg* (million ton/yr)	9.2	--	8.8	8.9	9.0	9.1
Total Emissions *reg* (million ton/yr)	--	7.3	7.3	7.3	7.3	7.3
Producer Surplus *nreg* (million $/yr)	0.0	--	67.0	62.5	45.1	26.1
Producer Surplus *reg* (million $/yr)	--	256.5	299.5	298.4	293.2	288.1
Consumer Surplus *nreg* (billion $/yr)	4.5	--	4.4	4.4	4.4	4.5
Consumer Surplus *reg* (billion $/yr)	--	4.2	4.1	4.1	4.1	4.1

Appendix 1: Multi-period demand function parameters

The inverse demand function in the cap-and-trade scheme, multi-period definition model is defined as:

$$p_{ij}^{e} = \Phi_{ij} - \frac{\Phi_{ij}}{\Psi_{ij}} \cdot d_{ij} \tag{28}$$

where the value for the parameters Φ_{ij}'s and Ψ_{ij}'s are defined as:

$\Phi_{ij} = 1000$; Ψ_{ij} as in Table A1:

Table A1: Demand function parameter assumptions

Ψ_{i1}	Ψ_{i2}	Ψ_{i3}	Ψ_{i4}	Ψ_{i5}	Ψ_{i6}	Ψ_{i7}	Ψ_{i8}
15000	3500	2600	2200	2000	1750	1650	1550
$\Psi_{i\,9}$	$\Psi_{i,10}$	$\Psi_{i,11}$	$\Psi_{i,12}$	$\Psi_{i,13}$	$\Psi_{i,14}$	$\Psi_{i,15}$	$\Psi_{i,16}$
1450	1375	1200	1250	1200	1160	1120	1080
$\Psi_{i,17}$	$\Psi_{i,18}$	$\Psi_{i,19}$	$\Psi_{i,20}$	$\Psi_{i,21}$	$\Psi_{i,22}$	$\Psi_{i,23}$	$\Psi_{i,24}$
1050	1010	980	940	900	850	780	620